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SOPWITH CAMEL VERSUS FOKKER DR.1: WHICH ONE TURNS THE BEST? AN ANALYSIS OF THE STATIONARY AND INSTANTANEOUS TURN PERFORMANCE FOR TWO OF WW1'S MOST FAMOUS AIRPLANES

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Abstract

While properties such as top speed and climb rate were of paramount importance and something the designers[1] of the time certainly strived for, WW1 is forever associated with dogfights in which scouts[2] whirl around in tight turns trying to get on each other's tails. This paper analyses two of the most famous aircraft of the Great War, namely the Sopwith Camel and Fokker Dr.1 from the perspective of turn performance. Which one was the best? How big was the difference? If one could turn tighter and faster than the other assuming the speed was kept constant was it also so if they were allowed to convert speed into turn rate? This paper will attempt to get to the bottom of these questions using a C++ simulation program developed by the author.

Introduction

The Sopwith Camel and Fokker Dr.1 while certainly familiar to most WW1 aviation enthusiasts, are perhaps best known to the general public through the comic strip Peanuts created by Charles M. Schultz. In Peanuts, Snoopy grapples with his eternal foe, the Red Baron, who more often than not manages to shoot a series of holes in Snoopy's Sopwith Camel doghouse drawing a "Curse you Red Baron!" from Snoopy. While the actual in-real-life Red Baron, Manfred Albrecht Freiherr von Richthofen, flew a number of different scouts during his career, he is certainly best known for flying his blood-red Fokker Dr.1. While the comic strip episodes paint a charming and innocent picture, the actual situation over the WW1 trenches was anything but rosy and although chivalry certainly still existed, the air war had by 1917 turned into a war of attrition in which the combatants fought bitter battles with increasingly higher performing scouts.

Anthony Fokker, circa 1912 (Left) and Thomas Sopwith circa 1910 (Right).

Photos: Wikimedia Commons.

In spite of the general design trend targeting higher speeds and climb rates by using more powerful engines and higher wing loadings, as exemplified by the water cooled in-line engined French SPAD, British S.E.5a and German Fokker D.VII, there were still even as late as 1917 and 1918 more all-round performing scouts powered by air-cooled rotary engines of lesser power and lower wing loading that to a large extent relied on their turning capability when competing with the former. Both the Camel and Dr.1 can be said to be part of this latter type and are certainly amongst the most well-known.

While the Camel and Dr.1 had some aspects like the low wing loading and a rotary engine in common, they were in a number of other respects quite different: The Camel was a for its time more conventional wire braced bi-plane while the Dr.1 was a cantilever triplane with no external bracing and instead relied on rectangular box spars housed inside the wings to carry both bending and torsional loads. In addition, while the Camel sported a for its time rather conventional wing profile, the Dr.1 incorporated a new type of thick wing profile that at the time was nothing short of revolutionary.

Fokker Dr.1.

Photo: Wikimedia Commons.

Sopwith Camel.

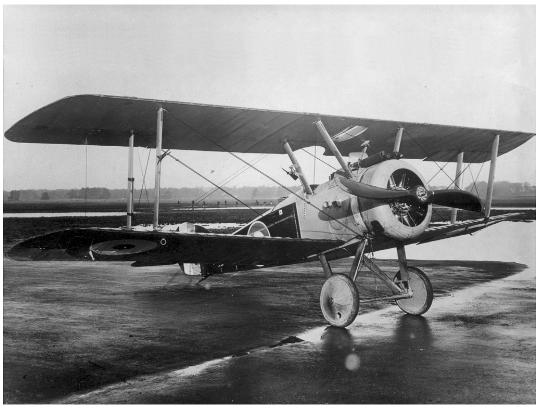

Photo: Wikimedia Commons.

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[1] Two of the most famous designers of the time were Thomas Sopwith who designed the Sopwith Camel and Anthony Fokker, the Fokker Dr.1.

[2] In WW1, What we today would call a fighter aircraft were known as scouts.

Wing profiles

The wing profiles of the Camel and Dr.1 were really of different generations: The Camel had a thin cambered wing profile rather typical for its time named the RAF-15 while the Dr.1featued a brand new cutting edge technology profile named the Göttingen 298.

To understand why the Göttingen 298 was so revolutionary, one needs to understand more about the state-of-the-art in wing profile design at the time. One of the major problems that plagued the designers of early wing profiles was that the effects of the Reynolds[3] (Re) number were not fully understood at the time. For example, typical WW1 type thin wing profiles suffer from an early leading edge airflow separation which unfortunately for the designers of the time, does not show up in low Re wind tunnel testing but only becomes evident at Re numbers closer to full scale conditions. Since wind tunnel testing at the time was done in such low Re numbers (in the range of 50 to a 100 thousand) the results erroneously indicated that thick airfoils produced much more drag than thin airfoils. This was due to the formation of a laminar separation bubble on the upper surface on thicker profiles which is a decidedly low Re number phenomena which would not have been there had they tested at higher Re.

However, in 1917, work by Professor Ludwig Prandtl at the University of Göttingen in Germany started to reveal the true potential of thicker wing sections leading to the development of profiles like the Göttingen 298 used on the Dr.1. The reason for these promising results were that in contrast to earlier testing, these new tests were carried out at a Re in the range of 2 million. This was sufficiently high to eliminate the misleading low Re results that made most other contemporary designers favour thin wing profiles like the Eiffel and RAF profiles that were so typical of the time. So while the lion's share of wing profiles used during the Great War may appear antiquated today, one should be careful not to judge WW1 designers penchant to select thin cambered profiles too harshly since most were simply not privy to any full scale Re wind tunnel data which would have revealed the true state of affairs.

Effects of wing configuration and span

The Camel's externally braced bi-plane wing arrangement was typical for its time both in terms of span, chord and the external bracing. However, on closer inspection it's obvious that the concept of streamlining had made an impression at the Sopwith works since both wing and landing gear struts and the bracing wire (rods actually) were all streamlined[4]. In addition, the Camel had an all-enclosing engine cowl[5] which has a significant effect on the zero lift drag (Cdo). This streamlining also paid off since the Camel even though it had a bigger wing area and external bracing, was even so slightly faster than the Dr.1 assuming the same power output and propeller.

The Dr.1 on the other hand had a triplane layout with two supporting struts and no panel type wire bracing. In fact, the first Dr.1 prototypes did not have any outer wing struts at all but were pure cantilever and the struts were added to the production model following accidents with the pure cantilever design.

In order to assess turn performance, the maximum lift coefficient (Clmax) of the complete aircraft needs to be estimated. Beginning with the two-dimensional[6] Clmax of the airfoils used on the Dr.1 and Camel, these are in the order of 1.70 for the Göttingen 298 and around 1.48 for the RAF-15. However, these numbers do not take into account the three-dimensional effects due to a limitation in span, i.e. due to aspect ratio[7] effects and interference between the wings in a bi- and triplane configuration. The Clmax estimates of the complete aircraft have therefore been reduced from these two-dimensional values as described in Table 1 below.

Definition of turn performance

First of all, what is to be compared needs to be defined: There are a number of variables that can be measured when comparing turn performance, the most important being turn rate, turn radius and turn time. While turn radius is sometimes also given in texts, this is actually not such an important metric since it is the turn rate and not the turn radius which decides how fast an aircraft can complete a full 360 degree circle. The most important turn related metrics are the sustained turn rate and the instantaneous turn rate:

The sustained turn rate is defined as the highest turn rate an aircraft can sustain without losing speed. There are two main properties that limit the sustained turn rate: The first being the amount of lift the wing can produce for a certain amount of drag and the other the engine power available to overcome this drag. Taking the Camel's sustained turn rate capability at 1 Km altitude in figure 2 as an example, the best sustained turn rate can be read off as slightly above 29 degrees/s. This is at the apex of two curves: The left hand curve is limited by the wings ability to produce lift and the right hand curve by the engine's ability to overcome drag due to the wings production of lift. From this follows that all other things being equal, if more power is added then there is an increase in turn rate which would in figure 2 be seen as the right hand part of the curve moving upwards to the right, meaning an increase in speed for best turn rate. Conversely, an increase in Clmax or wing area moves the left hand part of the curve upwards and to the left meaning that the best turn rate is attained at a lower speed for a given power.

The instantaneous turn rate is the turn rate the aircraft can achieve without any concern given to how fast the aircraft decelerates. In this case the aircraft does not have the power to generate enough thrust to balance the increase in drag and the pilot accepts a loss in speed in order to increase the turn rate to a value higher than the limit set by the sustained turn rate. The instantaneous turn rate is thus not limited by power, but either by the limit load factor, or if this is sufficiently large, by the product of the aircraft's Clmax and wing area. However, irrespective of which forms the limiting factor, an instantaneous turn is characterized by a loss in speed, hence the name instantaneous. As the speed drops the pilot is then faced with two options: Either keep the plane at Clmax and thereby accepting a continuous drop in speed or, when the speed has dropped to that for the best sustained turn rate, unload the plane and keep it at the speed for best sustained turn rate. Both principles are usable in air combat and the former may be used to attain a position for a shot at the expense of speed while the latter is used to retain energy and maintain the best possible turn rate. In this paper the latter scenario is assumed, i.e. that the pilot upon decelerating to speed for best turn rate unloads the airplane and capitalizes on a superior stationary turn rate to win the day.

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[3] The Reynolds number is a dimensionless number that gives the relationship between dynamic and viscous forces through the quotient of: The product of the speed and a reference length (usually the wing chord) divided by the kinematic viscosity.

[4] Streamlining bracing rods may seem excessive but in fact a round profile wire has roughly the same drag as an airfoil circa 10 times as thick!

[5] Compare the so-called Townend ring or the NACA cowling introduced in the 1920s.

[6] The two-dimensional (2D) maximum lift coefficient is the number that would be recorded in a wind tunnel for a wing model spanning the walls and can be understood as the Clmax for a wing of infinite span.

[7] The aspect ratio is a dimensionless value defined as the square of the span divided by the wing area.

Both the sustained and instantaneous turn rate usually fall off with increasing altitude which is only natural given that the air density goes down with increasing altitude. This has two effects on the airplane: One is that the power goes down since the engine breathes in less dense air and consequently produces less power[8]. The other is that the wings ability to produce lift is directly proportional to the dynamic pressure which in turn is the product of the air density and the square of the true air speed (TAS). In addition, while the engine's power is independent of speed the usable thrust is inversely proportional with the speed meaning that it goes down as the TAS goes up. All these factors combine to reduce the aircraft's turn performance as the altitude goes up which holds true for basically all propeller driven aircraft.

Verification of simulation model

The simulation code used for the comparisons in this paper is an adaptation of a Simula program the author coded in the 1980's for a Master's thesis which studied the influence of external stores on fighter jet aircraft. The program was later converted to C++ and modified to incorporate propeller aircraft and while the code does account for compressibility[9] effects, these do of course not make themselves known in this WW1 turn performance comparison. The atmospheric model used is standard atmospheric conditions assuming a sea level temperature of 15 degrees Celsius.

To estimate aircraft performance, the program accesses data such as zero lift drag coefficient (Cdo), maximum lift coefficient (Clmax), Oswald factor (e), propeller efficiency (η) etc. as a function of Mach number stored in vectors and structs and interpolates between data points to arrive at pertinent aircraft characteristics for any particular flight condition. The code then iterates the variables until a balance is achieved within a predetermined range and then list the output in tabular format. This output has then been post processed and used to generate the figures as presented in this paper.

The core part of the simulation code that calculates speed, acceleration times, climb rates, climb times and stationary and instantaneous turn performance has been extensively verified for WW2 aircraft for which there exists a wealth of reliable data, e.g. as can be found at Mike Williams and Neil Stirling's excellent website www[dot]wwiiaircraftperformance[dot]org.

However, data for verification of WW1 turn performance is much more scarce and for the data as presented in this paper, alignment was done using the only currently known set of data that is deemed sufficiently reliable: Namely NACA technical report 174[10] which has a detailed analysis of the Siemens Schukert D.IV's turn performance. There does exist other sources of turn rate data from trials with modern WW1 scout replicas but the only such tests known to the author either suffer from unreliable speed and altitude recording and some are not done at a constant speed meaning they are more instantaneous than stationary in character and therefore rendering them difficult to use as a basis for simulation model verification.

An interesting source of information on the Sopwith Camel is an aviation symposium lecture[11] from 2014 by the late aviator Javier Arango in which he details his experiences flying the Sopwith Camel from a series of trial done to determine its flying characteristics. In these trials, flight data was logged using data recording equipment that captured pertinent parameter values every quarter of a second and Mr. Arango's presentation of facts in this lecture indicates that these trials were done to the highest level of scientific standards and therefore a valuable source of data.

In the lecture, Mr. Arango mentions that gyroscopic forces are sometimes highlighted in historical accounts to prop up a supposedly much better turn time to the right compared to the left for the Camel but that such accounts are most likely more due to the difference in gyroscopic forces experienced when entering the turn in different directions as opposed to the actual turn rates experienced once established in the turn since gyroscopic forces will only result in somewhat different control surface deflections needed to maintain the turn depending on direction. In fact Mr. Arango was quite adamant in his description of his flight tests on this point: The Camel's stationary turn times measured in the trials was exactly the same (16 s) in both directions. Again, this should of course not be confused with how easy it is to establish a turn but it's still an important piece of the puzzle given the Camel's historic reputation to turn much better to the right rather than the left due to gyroscopic forces. However, it has unfortunately proven difficult to pin down the exact conditions and type of engine (Gnome, Le Rhone or Clerget) used during the these trials making it difficult to use these turn time numbers for simulator verification purposes.

On a tangent, one very interesting point brought up by Mr. Arango in the lecture was that only about 60% of the gyroscopic forces measured (in total 303 ftlb for the 160 hp Gnome) was due to the engine while the propeller accounted for the remaining 40% meaning that while there certainly is a difference between WW1 rotary and in-line engine scouts on this point, the difference was not as large as it may appear intuitively watching a rotary engine at work.

Another data point and piece of the puzzle that Mr. Arango provided in the lecture is a climb rate measurement of 1700 fpm for his Sopwith Camel which is also close to the sea level climb rate the simulation model used to derive the turn performance as outlined in this paper predicts which is 1719 fpm assuming the same power setting. Later in this paper is a whole chapter covering the Sopwith Camels's turn and handling characteristics in more detail based on an unpublished sixteen page essay written by Javier Arango prior to his tragic accident in a Nieuport 28 replica in April 2017.

As mentioned earlier, the most solid and reliable turn performance validation data available is the NACA report TR-174 which details the turning performance of the German Siemens Schukert D.IV scout. This aircraft was a late entry into the war and by many accounts a very popular machine with its pilots. Setting handling characteristics aside, one can also understand this by looking at the performance numbers, especially for the Siemens Halske SH IIIa powered variant which had a sea level continuous rating of 160 hp and up to

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[8] General rules usually have exceptions: So-called "overcompressed" WW1 engines like the Mercedes III.aü could to some extent compensate this loss at lower altitudes.

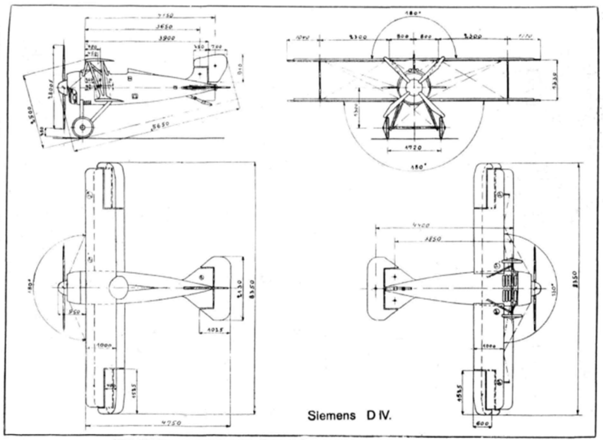
[9] The C++ model does take propeller tip Mach effects into consideration but this is more of a factor in WW2 aircraft simulation and basically negligible in this WW1 aircraft comparison.

[10] Airplanes in horizontal curvilinear flight, Heinrich Kann, NACA TR-174, January 1924. Translated from German Techniche Berichte III, by Heinrich Kann, 1918.

[11] A lecture by Javier Arango detailing his Sopwith Camel trials can be found on YouTube: WWI Aviation Symposium (1/4): Dr. John Morrow and Javier Arango.

200 hp for short periods. The Siemens Schukert D.IV had by some accounts a top speed of more than 190[12] Km/h and a for its time a very respectable climb rate reaching 6 Km in just 15.5 minutes.

Siemens Schukert D.IV



THE SIEMENS SINGLE-SEATER.—Side and front elevations, and plans from above and beneath.

Photo: Drawing original from Flight Magazine March 1919.

The reason for modeling the D.IV scout with a 200 hp sea level power setting in the C++ simulation is that this was the assumed power setting in TR-174. Figure 1 below shows a couple of figures from TR-174 which detail the turn time and turn radius as a function of altitude for the D.IV in the upper figure 7 and for three unidentified Entente scouts in figure 8 below:

Figure 1:

Fig. 7 & 8

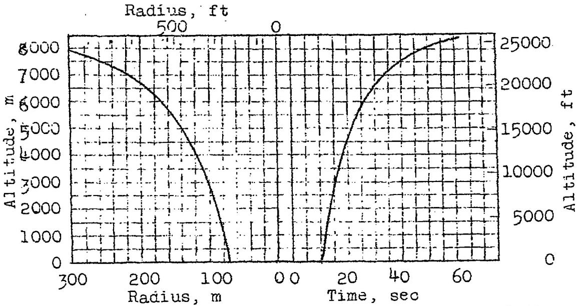


Fig. 7 Time required for completing a circle and the radii for the S.S.W. DIV airplane plotted against the altitude at an angle of attack of 12°

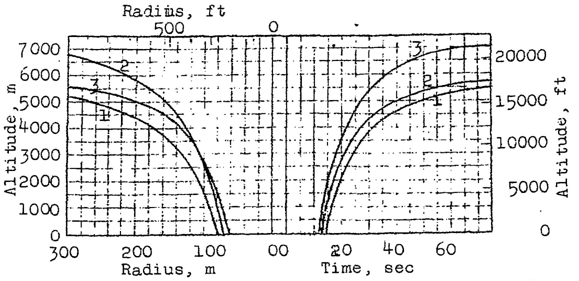


Fig. 8 Time required for completing a circle and the radii of the turn for three foreign airplanes, plotted against the altitude with the angle of attack at the ceiling.

Interesting to note is that while the D.IV is somewhat better at sea level with a sustained turn rate of around 10 s compared to the two of the Entente scouts at around 12.5 s while the third needs 15 s, the D.IV is markedly superior at higher altitudes. That the D.IV is so much better at higher altitudes is due to the high effective aspect ratio which in turn is a result of the comparatively low span loading and especially the high aspect ratio of the wings themselves.

Assuming the same wing area, weight and reduction of power with altitude as in NACA TR-174 the C++ simulation gives a turn rate of 10.4 s at sea level, 15.2 s at 3 Km and 26.9 s at 6 Km which is in reasonably good agreement with the numbers that can be read off in NACA TR-174's figure 7 above.

With the above as support for validating the basic C++ model, the Camel and Dr.1 was modeled using the same set of parameters but with the values appropriate for the these aircraft. Table 1 below summarizes the aircraft specific parameters that were used:

Table 1.

Parameter	**Sopwith Camel**	**Fokker Dr.1**
Wing area total	22.43 sqrm	20.02 sqrm
Weight[13]	672 Kg	575 Kg
Lifting exposed wing area	21.46 sqrm	18.66[14] sqrm
Wing loading	30.0 Kg/sqrm	28.7 Kg/sqrm
Physical wing span	8.53 m	6.22 m
Effective span	9.58 m	7.44 m
Effective span loading	70.1 Kg/m	77.3 Kg/m
Aspect ratio factor[15]	1.26	1.43[16]
Maximum lift coefficient profile	1.48	1.70
Maximum lift coefficient aircraft	1.05[17]	1.16[18]
Sea level power (hp) assumed in simulations	130 hp Clerget delivering 126 hp at 1250 rpm	110 hp (Nominal) Le Rhone delivering 122 hp at 1200 rpm
Power loading Kg/hp	5.33 Kg/hp	4.71 Kg/hp

While there is more data available to tune the zero lift drag coefficient (Cdo) for the Camel, this proved more problematic for the Dr.1 as there are conflicting speed values, especially concerning the sea level top speed. However, based on the data deemed most reliable, the Cdo in the C++ model has been tuned so that the Camel delivers 113 mph at 10,000 ft (182 Km/h at 3048 m) while the Cdo for the Dr.1 has been tuned to target the often quoted 165 Km/h[19] top speed at 4 Km altitude with the Oberursel II assumed to be delivered 122 hp at sea level at 1200 rpm. Using these data points as input, the resulting top speeds at sea level are 175 Km/h for the Dr.1 and 187 Km/h for the Camel.

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[12] The author has found no measurements for top speed but the required top speed (Erforderet) was 190 Km/h.

[13] Note that Dr.1 full fuel load is only 72 liters while Camel fully fueled carries 168 liters.

[14] Includes the landing gear wing area as per the German Baubeschribung Fokker Dr.1 from 1917.

[15] Based Ai/A from Fluid Dynamic Drag, Sighard Hoerner, 1965, Page 7-12 Figure 19.

[16] This value may seem high (Aspect ratio factor based on upper to lower wing gap) but actually correlates to what is needed to get climb and ceiling figures for the Dr.1 right in the simulations.

[17] Based on NACA report 279, VDT results for 3 British airplanes, G. Higgins, L. DeFoe and W. Diehl states Clmax 1.05 for flight test on a Bristol Fighter with the RAF-15 wing profile.

[18] The dangers of stalled flight, NACA report 52, L Hopf, 1920 states Clmax Fokker D.VII=1.22. Reduced by 5% to account for more wingtips on a triplane results in estimated Clmax=1.16.

[19] Based on manufacturers data. However, 1918 measurements by Flugzeugmeisterei der Idflieg indicated a lower top speed.

Another data value in the table that merits mentioning is the estimated Clmax for the Camel (See footnote 17) which is deemed reliable since it was measured in NACA's VDT wind tunnel at a sufficiently high Re to capture Re effects.

In this table are two key metrics that usually indicate superiority in turning performance and these are the wing- and power loading. Both these are in the Dr.1's favour: It has a more than 4% lower wing- and 12% lower power loading. However, even with these two advantages in the bag the simulations will show that the Dr.1 still comes up short at higher altitudes due to its very low aspect ratio and 10% higher effective span loading.

With the benefit of hindsight, the detrimental effects of a high span loading is of course easy to point out but as the commissioning of the Fokker Dr.1 shows, the effects of aspect ratio were not understood to a sufficient degree at the time. If the Germans instead had ordered a scout using the same wing area but instead spread out on two wings with a higher aspect ratio it would have had basically the same weight and speed performance but with a significantly better turn rate, ceiling and better climb rates at higher altitudes all with the same engine. The Siemens Schukert D.IV is actually a good example of how (given a certain wing area) to make an effective bi-plane design simply by distributing the wing area on a longer span with a shorter cord.

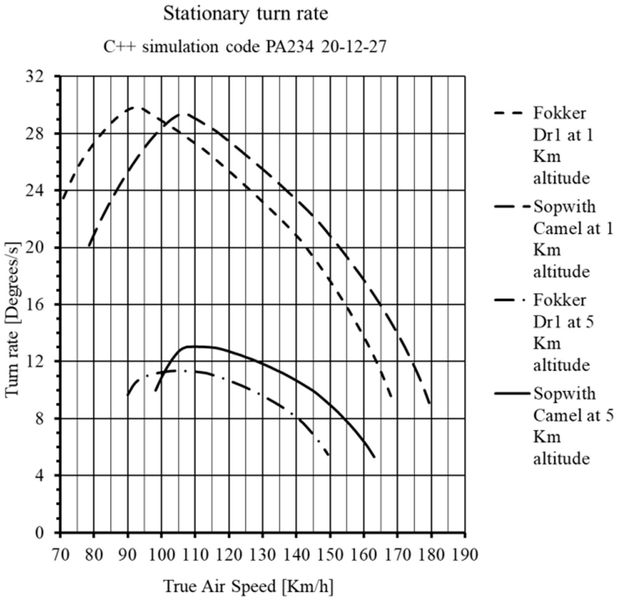
The term "Effective span" in the table above can be calculated using the "Aspect ratio factor" in the same table and is quite useful to get an indication of how two aircraft compare in terms of induced drag. The number should be understood as the span of a monoplane that is equivalent to a bi- or triplane with the same wing area in terms of induced drag. As the induced drag is inversely proportional to the span, it follows that a large effective span is a major asset for turning and comparing the Camel and Dr.1 on this point indicates a staggering 29% advantage for the Camel. It is also this difference that gives the Camel its edge in turns at higher altitudes and more than compensates for the poorer wing- and power loading numbers.

Another aspect that proved important for the turn performance in the simulations was the power available: While this can be readily understood for the sustained turn rate, the analysis showed that it also had a pronounced effect on the instantaneous turn rate. (See figures 4-7) and the simulations really highlight how fast a WW1 era scout decelerates due to what by today's standards can only be described as a horrendous amount of induced drag.

Sustained turn rate comparison

When comparing the maximum sustained turning capability (Figure 2 below), the aircraft are basically on par at sea level but with an increasing edge to the Camel as the altitude goes up. However, just comparing maximum turn rate is misleading since the Camel actually dominates most of the speed range and as long as the Camel pilot does not let himself be drawn into going too slow he can outturn his opponent. On the other hand the thick Göttingen wing profile gives the Dr.1 very benign post-stall characteristics and excellent low speed controllability[20], even to the point of so-called propeller hanging making the Dr.1 a very potent machine in the low speed left hand part of the figure below.

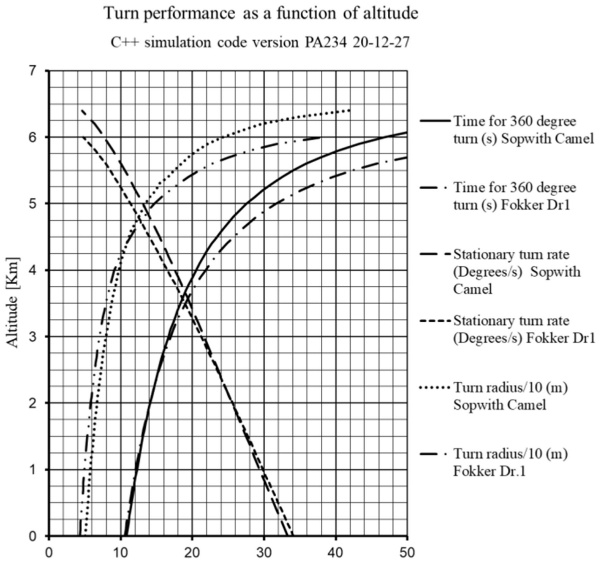
Figure 2:



Maximum turn rate as a function of altitude

Figure 3 below show that while the Camel and Dr.1 are close in stationary turn performance, the Dr.1 has a slight edge at sea level but has to concede this as the altitude increases due to the Camel's higher aspect ratio. That this is the dominating factor in determining turn performance can be concluded since it outweighs the Dr.1's advantage both in wing- and power loading.

Figure 3:



Instantaneous turn rate comparison

Comparing the Camel's and Dr.1's instantaneous turn performance is a valid exercise since in many cases aircraft are at higher speeds when sharp turns are initiated, e.g. when an aircraft is "bounced" by an attacker a typical defensive manoeuvre is to break into the attacker in a tight turn sacrificing speed for turn rate.

In the instantaneous turn scenarios outlined below, both the Camel and Dr.1 are able to utilize the maximum lift the wings can provide since neither aircraft will generate a g-load greater than the permissible even when the wings are at Clmax. The German design[21] rules varied during WW1 but in the later stages when the Dr.1 was designed the requirement for scouts were between 6 g's (1916) and 5 g's (1918). For the Camel, a Royal Aircraft Establishment (RAE) report[22] from 1920 gives the limit load factor as 5.4 g's.

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[20] Source: Information provided to the author by Mikael Carlson, owner of the world's most accurate Fokker Dr.1 replica. Website with more information: www[dot]aerodrome[dot]se.

As can be seen in the 5 Km altitude scenario (Figures 4 and 5 below), the Dr.1 slows down very quickly when performing an instantaneous turn starting at Clmax. This behaviour is markedly different from a typical WW2 fighter aircraft which not only typically has more than ten times the power but also a much higher wing loading and consequently will take much longer time to slow down. For the Dr.1 however, the result of trying to make a quick turn is akin to hitting a brick wall: The speed drops dramatically and it takes just a few seconds to reduce speed down to the speed for best sustained turn rate. Consequently, while the Dr.1's instantaneous turn performance judged solely on the two-dimensional Clmax and wing loading may at first glance appear impressive, it cannot capitalize on this since the Clmax for the complete aircraft is so much lower and that the speed drop at higher Cl is so dramatic. In fact as picture 5 shows, the Fokker Dr.1 loses nearly 40% of its initial 165 Km/h speed in just 7 s.

This means that the Dr.1 pilot needs to unload from a higher load factor to the sustainable 1.15 g already 7 s into the turn in order not to drop below the speed for best turn rate. The Camel on the other hand retains energy better and it's not until 17 s into the turn that the Camel pilot needs to unload slightly to transition to a stationary turn rate turn.

That the Dr.1 needs to unload so much quicker than the Camel, is caused by two factors: The first is the short effective span and the second is a higher Clmax. Since the induced drag is proportional to the square of the lift coefficient and inversely to the aspect ratio these effects combine to produce the faster drop in speed.

The Camel on the other hand has both a higher aspect ratio and a lower Clmax leading to a more gradual reduction in speed. In fact the Camel can at this altitude almost sustain a stationary turn at Clmax which then explains why the Camel needs to do only a slight load factor reduction far into the turn while the Dr.1 needs to do a larger reduction at a much earlier stage.

Figure 4:

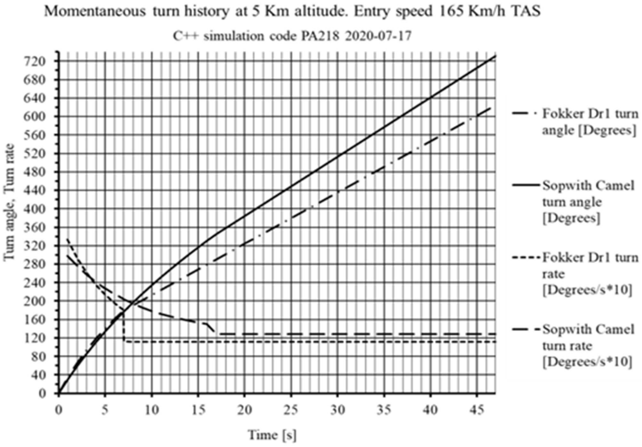
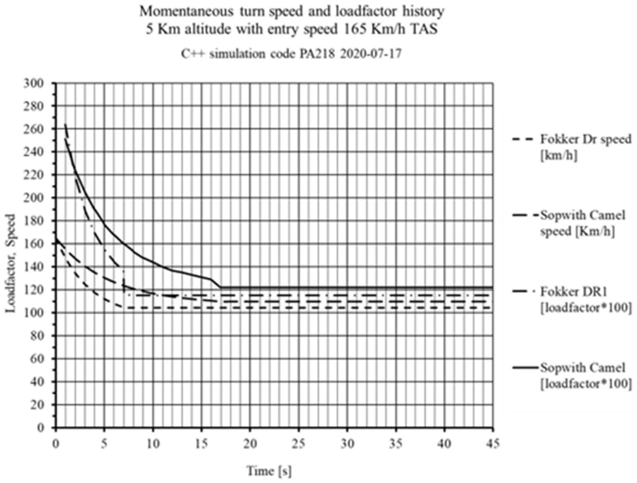


Figure 5:

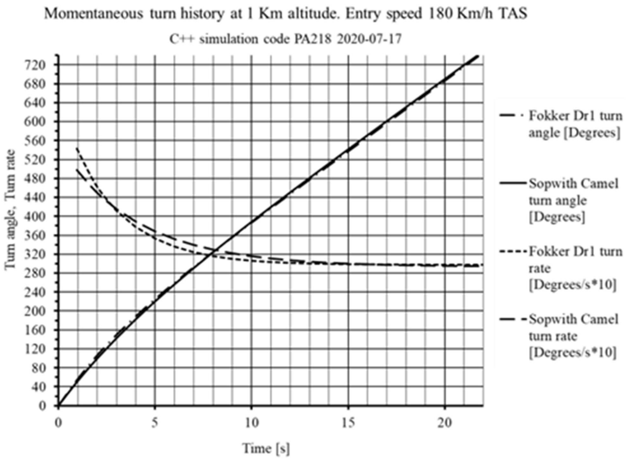


In this scenario the Camel needs about 46 s to turn two full circles while the Dr.1 manages 613 degrees (circa 15% less) in the same time. Since the stationary turn rate difference at this altitude is about 1.73 degrees/s the Camel then needs an additional 2 minutes and 26 seconds (circa 5.3 turns) before it ends up behind the Dr.1.

Moving the comparison to lower altitudes (Figures 6 and 7 below), at 1 km altitude both the Camel and the Dr.1 can sustain Clmax and consequently do not need to unload at all. In fact, looking at the figures, it's remarkable how evenly they are matched even though they are so different in their layout. In fact both the Camel and Dr.1 do a 180 degree turn in about 4 s and both finish their first complete circle after only 9 s.

The figure also reveals that while the Dr.1 does have a slightly faster turn rate for the first couple of seconds, after that the Camel's higher aspect ratio begins to tell and the Dr.1's turn rate falls behind the Camels. However, the difference is minute and for all intents and purposes the two can be said to be equal when it comes to instantaneous turn performance at this altitude.

Figure 6:



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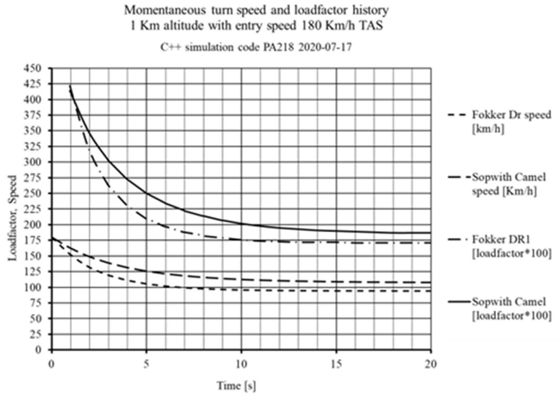
[21] NACA report 143, Analysis of stresses in German airplanes, W. Hoff, 1922.

[22] RAE R&M 670, The maximum angular velocity of aeroplanes, F.H. Bramwell, 1920.

Figure 7:



So, to sum up, both the sustained and instantaneous turning capabilities of the Camel and Dr.1 are about equal at low altitude while at higher altitudes the Camel holds a slight advantage.

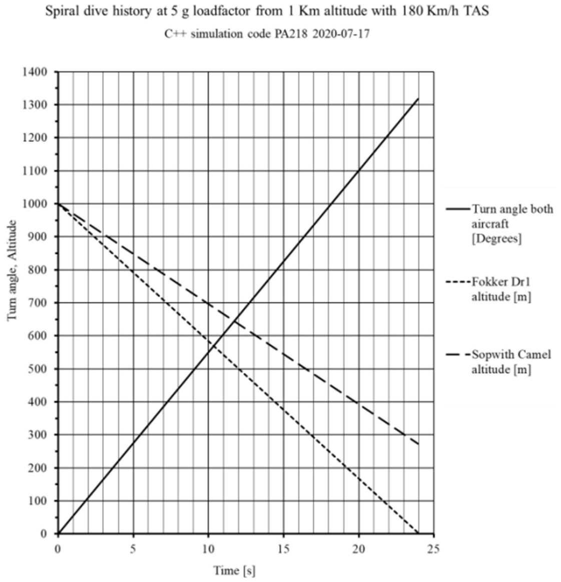
Spiral dive performance

In figure 8 below the turn angle and resulting loss of altitude as a function of time is shown for both the Camel and Dr.1 in a scenario where both aircraft start off at 1 Km altitude and maintain a constant 5 g's at 180 km/h TAS. Note that since both aircraft maintain the same g-load and speed there is no difference in the turn angle as a function of time and both can be shown with the same line.

As can be seen from the simulations, both aircraft need a high rate of decent in order to maintain the targeted speed and g-load. Of note is that the Dr.1 loses altitude faster than the Camel due to its higher induced drag and that after approximately 24 s when the Dr.1 has reached ground level, the Camel is still at an altitude of close to 300 m due to its lower span loading.

This spiral dive example is of course purely a theoretical exercise to compare the airplanes since no pilot would in real life fly at 5 g's for 24 s in a WW1 scout! However, the figure does for example illustrate that maintaining 5 g's for 2 s would cause a Dr.1 to lose about 100 m in altitude while a Camel would lose about 20% less due to the more efficient wing planform.

Figure 8:



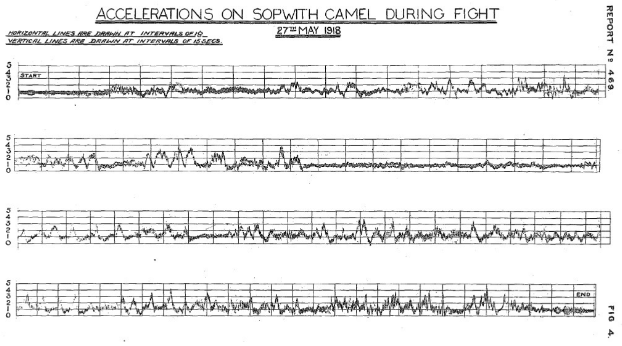
Sopwith Camel in flight g-loads measurements

A RAE report[23] from June 1918 documents the g-load history for a number of mock dogfights between different aircraft. One set of trials was done between two Sopwith Camels, the measurements for which are shown below in figure 9. Interesting to note is that higher g-loads are only sustained for very short durations, in the order of one or two seconds. Also noteworthy is that in general, the g-loads are in the order of 2-3 g's and only a few spikes reach as high as 4 g's.

In light of the simulations showing just how quickly the aircraft lose speed at higher g-loading this does not come as a surprise and these measurements do therefore to some extent support the findings in this paper since the RAE report did not record any occurrence of a higher g-load being sustained for any extended period of time just as would be expected given the rapid decelerations shown in figures 4-7.

However, higher g-loads are of course possible as shown in the spiral dive scenario depicted in figure 8 but these manoeuvres result in substantial losses of altitude: As an example, sustaining a g-load of 5 g's for 3 s would results in a 100 m altitude loss for a Camel which would not be a wise thing to do in a combat situation where both aircraft are trying to maintain energy which is then again most likely why the mock combat recordings from R&M 469 in figure 9 below only show high g-loads being performed for very brief periods of time.

Figure 9:



Sopwith Camel handling and turn characteristics

This chapter is based on an unpublished essay by the late Javier Arango generously made available by his widow via aviation journalist Peter Garrison. The essay is a great read and provides a wealth of information about handling characteristics and comparisons to anecdotal evidence. However, due to the limited space, only parts can be included in this paper. Reading the essay, I found this passage from the conclusions especially moving:

”WWI airplanes can act as a Rosetta Stone, helping us understand the past by deciphering the meaning of their pilots' words. Restoring the airplanes, working with them, and flying them also teach us that these airplanes were very much extensions of their pilots. The relationship between a pilot and his flying machine in WWI was still symbiotic. The capabilities of each airplane depended on the skill of its pilot, and what the pilot dared to do depended on the characteristics of his airplane.”

This observation is of course not only applicable to the Sopwith Camel and familiarity breeds confidence in any plane but it bears highlighting since it seems that while the Fokker Dr.1's stall is benign, the Camel's is not according to

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[23] Report on measurements of acceleration on aeroplanes in flight, G. Searle and W Cullimore, RAE R&M 469, June 1918.

Reno Air Race and stunt pilot Chuck Wentworth who also flew Mr. Arango's machines. Consequently, it's not unlikely that the average Dr.1 pilot would feel more comfortable than a Camel pilot pushing the plane to the very edge of stall which is also what's needed in order to attain the peak turn rates. Later in this chapter the effects of aileron, rudder and elevator deflection will be covered in more detail but on the subject on turns, below are two quotes from the essay that are especially interesting:

"Of the many manoeuvres we tested, the most revealing was the turn. In this essay I will discuss what we learned about the Camel's turning behaviour. Concentrating in great depth on turning alone will best illuminate not only the controversies about the Camel but also our flight-test findings and how they relate to physical design features of the airplane."

"Many of the Camel crashes occurred while it was turning. So we wanted to try to decipher what exactly made it simultaneously so lethal and so effective."

Leaving turns aside for the moment, in the essay Mr. Arango makes a point of stressing the Camel's agility and likens flying it to riding a bicycle and that it was exceptionally responsive and would feel like an extension of his body. It would turn just fine in both directions and the gyroscopic forces were not even noticeable. However, not all of his observations about the Camel are rosy:

"The Camel has no control harmony. The elevators are excessively light and responsive. The rudder is powerful but has no feel. The ailerons are very heavy and don't seem to do much, except the opposite of what you want. The pilot needs to continually move all the controls all the time with varying degrees of force just to keep the airplane going straight. The Camel has no stability, so it keeps wandering about all over the sky."

While the essay is mainly focused on the Camel's handling characteristics, Mr. Arango several times points out the problem of terminology and that pilots of the past and present sometimes mean different things using the same words. As an example, he mentions the term "turn" and that for WW1 pilots this could mean both what we today would call a snap roll or a descending spiral depending on context. In addition, he points out that based on his experience, following these century old pilot's instructions to the letter would in some cases produce "very, very unpleasant results" but at the same time tempering these observations by explaining how these statements from the past should be interpreted in a more modern context.

The Camel test flights were done with a data recording device activated and various manoeuvres designed to isolate and measure the effect of different control inputs. Interesting to note is that the flights were done with only a partly filled fuel tank but that even so the resulting balance was in the order of 31 % MAC which is very close to Mikael Carlson's Fokker Dr.1 at 32% MAC meaning that both aircraft can on theoretical grounds be expected to be very lively in pitch. Extrapolating on this information it's also easy to understand just how unstable in pitch a Camel could become if you topped off the tank!

Returning to the test results and beginning with the ailerons, when attempting to roll to the left with aileron input only, the nose swings violently to the right so that when a roll angle of 30 degrees to the left has been attained, the yaw angle to right is all of 30 degrees due to the excessive adverse yaw. In a modern plane the nose displacement tends to swing back but in this case the nose stayed where it was resulting in zero turn rate to the left! According to Mr. Arango, this unusual behaviour is most likely due to an unfortunate design decision to hinge the Camel's aileron on the lower edge opening up a wide gap that resulting in what he called astonishingly powerful adverse yaw.

As opposed to the ineffective ailerons, these are Mr. Arango's own word on the effects of applying left rudder: "The Camel responded immediately to the rudder input by correctly yawing its nose to the left. The wings quickly rolled left and automatically established a 30-degree bank. Surprisingly, the nose rose on its own, which is what a pilot usually needs to do by hand in order to make the airplane turn tightly without losing altitude. The Camel responded to a left rudder deflection by establishing a very nice turn to the left without further action by the pilot."

However, it turns out that the results of applying right rudder are quite different: "Next, encouraged by the good results obtained by the application of left rudder, we tried a right-rudder input. I truly expected the Camel to do exactly what it had done before, except to the right. The Camel immediately responded to the rudder by yawing to the right, but then it acted strangely. The bank was only partial, never exceeding 20 degrees, and the nose dove down instead of rising." Mr. Arango then goes on to explain that this leads to an uncomfortable flight condition with not much bank but with a great yaw angle and a nose down attitude.

As an outside observer, it's here interesting to note that while the Camel yaws more rapidly to the right than to the left, just as claimed by contemporary authors, its roll rate was quicker to the left than the right contradicting some historical statements that the Camel has trouble rolling to the left.

Next an observation on the effects on pitch: "The biggest asymmetry, however, is in pitch. Turning the left, the Camel's nose came up; turning to the right, it went downward. Modern airplanes do not do this and certainly not at the violent rates the Camel displayed."

Finally, the overall effects of rudder input are summed up: "It is most interesting to examine the consequences of a rudder input five seconds into the turn. Turning to the left, the airplane is adequately banked and turning in the intended direction, and its nose has descended from the initial pitch-up back to level flight. This is a very benign and controlled turn. But to the right, the airplane is turning more quickly, yet without adequate bank angle. The result is very unnerving. An airplane yawing quickly without enough bank angle is tending toward an uncontrolled and dangerous spin, and when its nose points downward it is in danger of entering a spiral in which its speed could quickly and dangerously increase."

On the subject of gyroscopic forces, there are a couple of interesting passages in the essay that I think are best conveyed word for word:

"While discussing with him [Peter Garrison] my own experience of flying the Sopwith Camel, I noted that most of the accounts of WWI pilots seemed to me very exaggerated. I thought the Camel was a challenging aircraft but one that behaved mostly normally. When Peter asked me about the effects of gyroscopic precession due to the rotating engine—a contentious topic blamed for numerous accidents in the Camel¬—I again told him that it was barely perceptible and could be mostly disregarded by the pilot."

"The Camel was thus not a defective aircraft that was susceptible to uncontrollable gyroscopic precession. In the most extreme manoeuvres it may have become uncontrollable, but so would most airplanes because of many other variables. The gyroscopic precession force in the Camel was not in itself the ultimate cause of such strange behaviour and of so many accidents."

Another note of interest related to gyroscopic forces is that Mr. Arango again highlights the problem of terminology and correctly interpreting pilot statements from this time period since it seems that when they said torque, many were actually referring to precession effects and not to what we today would refer to as torque, e.g. the engine torque that turns the propeller.

Mr. Arango goes on to say that the high accident rates probably had less to do with the Camel being extremely difficult to fly but rather more to do with the pilots simply not being familiar enough with the aircraft and that inexperienced pilots may have become task-saturated and used inappropriate elevator and rudder combinations when attempting to correct the supposedly deadly right hand turns. Whatever the actual causes of the high accident losses were, Mr. Arango is quite clear in the essay that the Camel is perfectly controllable as long as you use the correct control inputs.

The trials also debunked the myth that the Camel's turn to the right and left differed so much that a pilot would prefer to do a 270 degree turn to the right in order to make a 90 degree left hand turn: The flight data recorded showed that when making steep turn to the left and right using appropriate control input, it took exactly the same amount of time to complete a full 360 degree turn in either direction, namely 16 seconds. However, in the same passage, Mr. Arango observes that the Camel was unstable in the turn and that quite different control combinations were needed but that he as a pilot thoroughly familiar with the airplane corrected these instinctively and that the substantial difference in control input depending on turn direction as witnessed in the recorded flight data surprised him.

Summing up, it seems that many of the quirks attributed to the Sopwith Camel from legend do not stand up to a closer scientific scrutiny and while the Camel certainly was a difficult aircraft to master, probably to a large extent due to the concentration of weight close to the C.G and the very low level of stability in pitch due to a very rearward center of gravity, the thorough testing performed by Mr. Arango proves that it was nonetheless an aircraft that was perfectly controllable given that the pilots who flew them had sufficient training and experience to use the right control combinations.

Fokker Dr.1 handling and turn characteristics

The author has had the good fortune to speak to the Swedish aviator Mikael Carlson who has taken pains to build what is arguably a carbon copy of a Fokker Dr.1 accurate down to the last nuts and bolts. Not only that, but he flies it in advanced manoeuvres as well meaning he is in a unique position to talk about the Dr.1's flying characteristics since this is not a replica but an actual reincarnation of the plane built and flown as it was in WW1.

Mr. Carlson's Dr.1 is also authentic in terms of instrumentation meaning there are no hard numbers on stall and maximum speed available since he flies the plane as it was flown back in WW1, i.e. by feel. Concerning turns, while he has not timed them, he says there is no marked difference in turn times left or right once settled into the turn but that the gyroscopic forces do help in establishing a turn to the right while opposing a turn to the left. He also confirmed that the Dr.1 slows down rather quickly in tight turns, just as predicted in the simulations.

Contrary to common belief, the gyroscopic effect in the Dr.1 is quite manageable and gyroscopic forces are in fact more pronounced in a North American P-51 according to Mr. Carlson who not only flies the Mustang but also the Hangar10 operated Messerschmitt Bf 109G-6 putting him in an authoritative position to judge these airplanes relative handling characteristics. Interestingly, another airplane he has flown that exhibits pronounced gyroscopic effects is not a rotary powered plane but surprisingly enough the jet powered de Havilland Vampire with its huge radial compressor. Returning to the Dr.1's gyroscopic precession characteristics, he said these are quite manageable unless at very low speeds close to stall and that consequently, he tends to lean a loop slightly to one side in order to have control of in which direction the Dr.1 departs should the speed become too low at the top of a loop.

The Dr.1's stall characteristics are very benign according to Mr. Carlson and in fact the aircraft does not have a pronounced stall point at all but kind of mushes when exceeding the stall angle of attack while still retaining good control authority which supports the popular legend that Fokker's thick winged Göttingen profiled Fokker Dr.1 and D.VII had the ability to hang by the propeller to catch an unwary Entente pilot from below.

In yaw the Dr.1 is neutral in directional stability meaning that if the pilot uses rudder to give the plane a certain yaw angle, it will stay there until the pilot actively uses the rudder again to bring it back on track lending credence to the Dr.1's purported ability to fly sideways while firing its guns.

When asked about the Dr.1's spin characteristics, Mr. Carlson said he has chosen not to explore this part of the envelope since the high rotational speeds in a spin would cause significant gyroscopic loads on the bearings of the engine which seems like a prudent precaution given how scarce and valuable these remaining original WW1-era rotary engines are.

A further note of interest is that he said that the aerodynamic overhang balances on the Dr.1's control surfaces work well and there is no tendency for overbalance within the flight envelope and that the aileron stick forces remain light allowing rolling manoeuvres even at higher speeds which is in stark contrast to the aerodynamically unbalanced ailerons on the Pfalz D.VIII[24] which he says are hard to budge at higher speeds.

Another interesting point regarding the Dr.1's aerodynamic characteristics is that it is tail heavy and given Mr. Carlson's quest for historic accuracy, his Dr.1 has been balanced as it flew in WW1 and the center of gravity is as far back as 32 % MAC which explains the significant down elevator needed on the Dr.1 to keep the nose down. In fact, he has equipped his Dr.1 with a bungee cord connected to the stick so that there is some level of trimming available to handle the stick forces needed to maintain the pronounced stick forward position needed to keep in level flight. With the center of gravity so far back he points out, the aircraft is basically unstable in pitch and needs to be flown pre-emptively at all times.

Taxiing is best done with helpers on the wings assisting in getting the aircraft in the right direction and lined up for take-of. There is however directional control available should it be needed, if the skid is unloaded and the engine gunned to get sufficient airflow over the rudder. Landing the Dr.1 should always be done as close to a three point landing as possible and into the wind using the elevator to push the tail down and get traction for the skid after touchdown. Crosswinds are to be avoided as far as possible and the plane is prone to ground looping and after touchdown some engine power and constant attention with the rudder is needed to maintain course. Attempting wheeler landings is off the table as it is an open invitation for a ground loop and consequently something he avoids doing in the Dr.1.

As a final note on handling characteristics, Mr. Carlson commented that pilots sometimes like to tell stories and that the Dr.1 is in fact not that difficult to fly as long as you have sufficient experience flying it. Different in the sense that other combinations of control movement are needed but as long as you are familiar with the airplane and the somewhat unorthodox engine control, it is not that much more difficult to handle than a more conventional plane. That however said with the caveat that the Fokker Dr.1 does require the pilot to handle it in the correct way and pay constant attention or, as he puts it, it will turn right back and bite you.

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[24] Mr. Carlson has recently built and is currently test flying a Pfalz D.VIII replica aircraft with an original Siemens-Halske Sh.IIIa engine.

Comparison of the aircraft's handling characteristics

Summing up on handling, the impression is that Javier Arango's statements about the Camel tie up rather nicely with Mikael Carlson's about the Dr.1: Both aircraft are perfectly controllable as long as you are familiar with their handling characteristics and don't mistreat them and that gyroscopic forces while certainly noticeable, are quite manageable. However, both also stress that the airplanes need constant attention or they will drift off on their own but that given enough practice, they are not difficult to fly. On a more detailed level, they both point out that neither the Camel's nor the Dr.1's rudder is self-centering and requires special care. However, one big difference that does stands out are the aileron characteristics: While Mr. Arango emphasizes that the Camel is best turned by the rudder, Mr. Carlson say's the ailerons on the Dr.1 are pleasantly light, effective and well balanced.

Conclusions

The simulation results were in some sense a surprise: Intuitively, the three stacked wings of the Dr.1 and the more modern thick wing profile exudes manoeuvrability and ability for tight turns. This has also been the Dr.1's legacy: Not only by popular myth but also as portrayed in more knowledgeable circles through the exploits of Manfred von Richthofen and Werner Voss's legendary dogfight on the 23rd September 1917 in which he single-handedly fought and holed eight British S.E.5a aces before finally succumbing to the uneven odds.

The key takeaways from the simulations is that WW1 fighters like the Camel and Dr.1 decelerate very quickly at higher g-loads and that even though there certainly is a significant rise in wing profile drag in steep turns when close to the aircraft's maximum lift capability, more than three quarters of the drag is still due to the induced drag which again highlights that the key to good turn performance lies in a low span loading.

Consequently, when the cold hard numbers are scrutinized in more detail, the Dr.1's aerodynamic Achilles's heel, the short span and resulting low aspect ratio, becomes apparent: There is no way around that such a high span loading will produce copious amounts of induced drag which is also what the simulations show.

So even though the Fokker Dr.1 possesses a more modern high lift wing profile, lower power- and wing loading, these advantages only go so far as to allowing it to match the Camel at low level while at higher altitudes, the higher span loading means that it has to concede the first place in turn performance to its most famous antagonist, the Sopwith Camel.

Author:

Anders Jonsson holds a Master of Science degree in aeronautical engineering from the Royal Institute of Technology in Stockholm, Sweden, specializing in aerodynamics and structural engineering. He is currently employed in the telecommunications industry working with 5G research and development. Prior to that he worked in the Swedish defense industry with aerodynamics, structural and systems engineering, project management and marketing for various Ericsson and SAAB owned companies working with electronic warfare and training systems both for vehicular and aircraft applications including the jamming pods U22, U25, U95 and the electronic countermeasures suites for the AJ37, JA37 Viggen and JAS39 Gripen aircraft.

Afterword

This paper contains a number of assumptions and estimates that quite possibly could benefit from being further reviewed and revised and constructive feedback is therefore most welcome on e-mail: ww1aircraftperformance[at]gmail[dot]com.

Revision handling and changelog

First revision: Compiled 4th July 2020.

Second revision: Updated 22nd August 2020 with special thanks to Mikael Carlson, builder, pilot and owner of the world's most accurate Fokker Dr.1 replica for providing input on the Fokker Dr.1's handling characteristics and to Florian Steiner, PhD, University of Zurich for input on maximum lift and propeller characteristics. Summary of changes: New chapter with Fokker Dr.1 handling characteristics added. Clmax for both aircraft has been reduced and propeller model for Dr.1 revised to capture that it used a more climb optimized propeller (diameter 2.62 m, pitch 2.3 m) compared to the Camel's 2.59 m by 2.65 m. Cdo for Fokker Dr.1 increased to target 165 Km/h TAS at 4 Km altitude.

Third revision: Compiled 10th December 2020. Updated with new reference (thanks to Yavor Dinkov, PhD, Technical University of Sofia) indicating that the previously estimated Clmax for the Fokker Dr.1 does not need to be revised: NACA report TM 52 "The danger of stalled flight and an analysis of the factors that governs it by L. Hopf from 1921 gives a Clmax=1.22 for Fokker D.VII. However, since the Dr.1 has more wingtips where lift goes to zero, the previously estimated Clmax of 1.16 seems reasonable. Clarified that the Siemens Schukert D.IV 190 Km/h top speed is a requirement and that the actual top speed was probably higher just as it was for measured climb rate. Clarified that the Sopwith Camel's estimated Clmax is deemed reliable since it is measured on a similar model with the RAF-15 wing profile at a sufficiently high Re number in the VDT wind tunnel.

Fourth revision: Compiled 15th February 2020. Added turn radius in turn rate with altitude figure 3. Modified text related to Cdo and Clmax estimates in table 1. Added text explaining that the Camel would do even better if Camel instead of 168 liters of fuel carried only 72 liters like the Dr.1.

Fifth revisions: Compiled 22nd May 2021. Added a Sopwith Camel handling chapter based on an unpublished essay by the late Javier Arango generously made available by his widow via aviation journalist Peter Garrison. Also removed usage of Sopwith Camel data for turn model validation since the previous assumption that this test involved the Gnome engine was probably not correct: According to Mr. Garrison, the test was most likely done with a Le Rhone engined Camel at an undetermined density altitude and consequently, since the details of these particular tests are not totally clear it has been removed from the paper.